

# HOLOGRAPHIC SPECTRAL FILTER

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## RELATED APPLICATIONS

**[0001]** This application is a divisional application of prior-filed co-pending non-provisional App. No. 09/811,081 entitled "Holographic spectral filter" filed 03/16/2001 in the name of Thomas W. Mossberg, said non-provisional application in turn claiming benefit of: 1) provisional App. No. 60/190,126 filed 03/16/2000; 2) provisional App. No. 60/199,790 filed 04/26/2000; 3) provisional App. No. 60/235,330 filed 09/26/2000; and 4) provisional App. No. 60/247,231 filed 11/10/2000. Said non-provisional application and each of said provisional applications are hereby incorporated by reference as if fully set forth herein.

## BACKGROUND

**[0002]** The field of interest is optical signal processing.

**[0003]** Spectral filtering is a very useful optical function that can be utilized to control the temporal waveform of pulsed optical signals, cross-correlate or otherwise process optical signals, and to differentially control and manipulate spectrally-distinguished optical communication channels, as found for example in wave-division-multiplexed (WDM) optical communication systems. Devices have been introduced over the years to perform spectral filtering, all of which have characteristic shortcomings along with their strengths. In many cases these shortcomings, including limited spectral resolution, alignment sensitivity, fabrication difficulties, high cost, and lack of flexibility, have prevented widespread application.

**[0004]** A spectral filtering device, according to the present usage, is a device that applies a fixed or dynamically re-programmable, complex-valued, spectral transfer function to an input signal. If  $E_{in}(\omega)$  and  $E_{out}(\omega)$ , respectively, represent Fourier spectra of input and output signals, computed on the basis of the time-varying electric fields of the two signals, and  $T(\omega)$  is a complex-valued spectral transfer function of modulus unity or smaller, the effect of the spectral filtering device (also called an optical processing device, OPD) can be represented as

$$E_{out}(\omega) = T(\omega) E_{in}(\omega) \quad (1)$$

**[0005]** The transfer function  $T(\omega)$  has an overall width  $\Delta_\omega$  and a resolution width  $\Delta_r$ , where the latter quantity is the minimum spectral interval over which  $T(\omega)$  displays variation (see Fig. 1), and is a significant measure of the transformation ability of a spectral filtering device. The physical characteristics of a particular spectral filtering device determine the range and types of spectral transfer functions that it can be configured to provide. We limit our discussion here to spectral filtering devices that act to apply a fully coherent transfer function, i. e. the device fully controls the amplitude and phase shifts applied to the input signal spectrum, except for an overall phase factor.

**[0006]** Spectral filtering devices can be utilized to transform input signals from one format into another, or to tailor their spectra to some preferred form. A spectral filtering device, according to the present usage, may or may not have the additional capacity to transform the spatial wavefront of input optical signals.

**[0007]** As a special case, if  $T(\omega)$  is set equal to the conjugate Fourier spectrum  $E_{ref}^*(\omega)$  of a reference temporal waveform, also called the design temporal waveform, the output field from the spectral filtering device is proportional to the cross-correlation of the input field with the reference temporal waveform. Temporal cross-correlation capability is widely useful in temporal pattern recognition.

**[0008]** The capabilities of a spectral filtering device can be utilized in multiple ways in communications systems, including signal coding and decoding for Code-Division Multiplexing (CDM), optical packet recognition, code-based contention resolution, as WDM multiplexers and demultiplexers, and as WDM add/drop multiplexers. Figure 2 depicts the encoding and decoding of optical signals in a CDM context. Data 202 is input through a first communication channel, and data 206 is input through a second communication channel. Data 202 passes through a spectral filter 204, which encodes data 202 with an identifying code. Similarly, data 206 is encoded with an identifying code by a spectral filter 208. The encoded signals are combined and transmitted over an optical transmission line 210. At their destination the encoded signals are split into two paths, 212 and 214. The upper path 212 feeds into a spectral filter 216, which imparts a transfer function that is the conjugate transfer function of the filter 204. The

1 output of spectral filter 216 is a signal comprising the superposition of data 202 and data  
2 206; however, due to the encoding imparted by spectral filters 204 and 208 and  
3 subsequent decoding by spectral filter 216, this output signal contains a component 218  
4 originating from 202 that has a specific recognizable temporal waveform, typically  
5 comprising a brief high power peak for each bit transmitted, along with a component  
6 220 originating from data 206. In the upper path, the component originating from data  
7 206 has a temporal waveform structure that can be discriminated against in detection.  
8 Typically, component 220 has no brief high power peak.

9 **[0009]** In similar fashion, the lower branch 214 feeds into a spectral filter 222, the  
10 output of which is a signal made up of the superposition of a component 224 originating  
11 from data 206, and a component 226 originating from signal 202. As before, the two  
12 signal components have distinguishable temporal waveforms, with the component from  
13 data 206 typically having a brief detectable high power peak while the component from  
14 data 202 lacking the brief high power peak, and hence remaining below a detection  
15 threshold. A key element in CDM detection is the implementation of thresholding in the  
16 detection scheme that can distinguish input pulses of differing temporal waveform  
17 character.

18 **[0010]** A variety of other CDM methods are known and, many of them having need for  
19 high performance spectral filtering devices. Some alternative CDM approaches operate  
20 entirely with spectral coding. Different applications for high performance spectral  
21 filtering devices exist. For example, spectral filtering devices capable of accepting  
22 multiple wavelength-distinguished communication channels through a particular input  
23 port, and parsing the channels in a predetermined fashion to a set of output ports, i.e.,  
24 a WDM demultiplexer, have wide application. This is especially true if the spectral  
25 filtering device is capable of handling arbitrary spectral channel spacing with flexible and  
26 controllable spectral bandpass functions.

27 **[0011]** A widely known approach to implementing coherent spectral filtering is a dual-  
28 grating, free-space optical design, shown schematically in Figure 3. Gratings 302 and  
29 310 are periodic, with grooves of constant spacing and amplitude. A first grating 302  
30 spectrally disperses an input signal, providing a mapping of frequency-to-position along

1 the x-direction of the filter plane. A lens 304 directs the signal to a planar phase and/or  
2 amplitude mask 306, varying in the x-direction, with  $\Delta_r$  representing the minimum  
3 spectral width over which the mask exhibits variation. A second lens 308 directs the  
4 output of the mask 306 to a second grating 310, which accepts the filtered spectral  
5 components that have passed through the mask 306, and maps them onto a common  
6 output direction.

7 **[0012]** The dual-grating, free-space spectral filtering device has limited appeal in the  
8 context of communication systems because of its physical complexity, sensitivity to  
9 precision alignment, relatively large insertion loss, and limited spectral resolution for  
10 gratings of tractable physical dimensions. In the dual-grating spectral filter described  
11 above, the gratings act only to apply and invert an angle-to-space mapping; no  
12 information specific to the transfer function to be imparted resides in the gratings. The  
13 mask 306 is necessary to impart the transfer function.

14 **[0013]** There is another class of spectral filters wherein the entire spectral filtering  
15 function is effected through diffraction from a single diffractive structure, having  
16 diffractive elements whose diffractive amplitudes, optical spacings, or spatial phases  
17 vary along some design spatial dimension of the grating. Diffractive elements  
18 correspond, for example, to individual grooves of a diffraction grating, or individual  
19 periods of refractive index variation in a volume index grating. Diffractive amplitude  
20 refers to the amplitude of the diffracted signal produced by a particular diffraction  
21 element, and may be controlled by groove depth, magnitude of refractive index  
22 variation, magnitude of absorption, or other quantity, depending on the specific type of  
23 diffractive elements comprising the diffractive structure under consideration. Optical  
24 separation of diffractive elements refers to the optical path difference between diffractive  
25 elements. Spatial phase refers to the positioning as a function of optical path length of  
26 diffractive elements relative to a periodic reference waveform. The spatial variation of  
27 the diffractive elements encodes all aspects of the transfer function to be applied. We  
28 refer here to diffractive structures whose diffractive elements (grooves, lines, planes,  
29 refractive-index contours, etc.) possess spatial variation representative of a specific  
30 spectral transfer function using the term "programmed." Programmed diffractive  
31 structures, i.e. those whose diffractive elements possess spatial structure that encodes

1 a desired spectral transfer function, have only been previously disclosed in the case of  
2 surface relief gratings, and in fiber gratings whose diffractive elements correspond to  
3 lines (or grooves) and constant index planes, respectively. Programmed diffractive  
4 structures known in the art do not provide for the implementation of general wavefront  
5 transformations simultaneously with general spectral transformations.

6 **[0014]** Programmed surface gratings and programmed fiber gratings are encumbered  
7 with severe functional constraints. A programmed surface-grating filter has a  
8 fundamentally low efficiency, and requires alignment sensitive free-space optical  
9 elements to function. Programmed fiber-grating filters produce output signals that are  
10 difficult to separate from input signals (since they can only co- or counterpropagate),  
11 and can only support a single transfer function within a given spectral window.

12 **[0015]** In 1998, Babbitt and Mossberg [(Opt. Commun. **148**, 23 (1998))] introduced a  
13 programmed surface-grating filter, either reflective or transmissive, whose diffractive  
14 elements (straight grooves) exhibit spatial structure, i.e., variations in diffractive  
15 amplitude, optical separation, or spatial phase, in the direction perpendicular to their  
16 length. A free-space implementation 400 of this device is schematically represented in  
17 Fig. 4. The diffractive elements (grooves) of the programmed surface-grating filter  
18 extend uniformly normal to the plane of the figure, while the diffractive amplitude, spatial  
19 separation, and/or spatial phase of the diffractive elements varies with position along  
20 the x-direction. A programmed surface-grating device can be produced by a variety of  
21 fast and economical processes such as by stamping, lithography, or masking  
22 processes. However, programmed surface-grating filters have a very serious deficiency  
23 in their intrinsically low efficiency. The profile of a programmed surface grating can be  
24 thought of as an assemblage of sine gratings, each of which maps one spectral  
25 component of the input signal to the output direction. Since the surface diffraction  
26 condition constrains only the surface projection of the input and output wavevectors,  
27 however, each constitutive sine grating interacts with all spectral components of the  
28 input beam, diffracting all but its design component into discarded output directions. As  
29 a result, the higher the complexity of the programmed transfer function (and therefore,  
30 the more sine components needed to describe it), the lower the efficiency of the  
31 programmed surface grating filter.

1 **[0016]** Fiber Bragg gratings, such as 502 illustrated in Fig. 5, have become an  
2 accepted component in optical communications systems. Programmed fiber Bragg  
3 gratings have been disclosed, and provide for higher efficiency and easier  
4 implementation than programmed surface gratings. Programmed fiber-grating filters are  
5 implemented in fiber links in the same manner as ordinary fiber-grating devices,  
6 typically using a circulator 504. Programmed fiber Bragg filters are useful, but have  
7 significant limitations. A primary drawback is that there is only one input direction 506  
8 and one output direction 508, those directions being antiparallel (transmitted signals are  
9 not often employed.) This means that a given programmed fiber-grating filter can be  
10 configured to produce only a single transfer function in a specific spectral region.  
11 Furthermore, a circulator 504, used to separate input and output signals is costly, and  
12 adds complexity to the overall device. Finally, programmed fiber Bragg gratings are  
13 time-consuming and labor-intensive to fabricate. The transfer function is typically  
14 imparted to the material via varying the material's index of refraction along the length of  
15 the fiber. Fabrication typically requires complex masking and high power ultraviolet  
16 exposure for extended time periods, or complicated ultraviolet holographic exposure  
17 apparatus with long exposure times.

18 **[0017]** There have been filters disclosed comprising systems of uniform diffractive  
19 elements, that offer the capability of applying a specific type of spatial wavefront  
20 transformation to input signals, but that do not possess the capability of implementing  
21 general spatial or spectral transformations. Spatial wavefront transformation capability  
22 enhances the capability of the device to accept signals from input ports and map them  
23 to output ports, without the aid of auxiliary devices to effect needed spatial wavefront  
24 transformations.

25 **[0018]** There remains a need in the art for spectral filtering devices that offer all of the  
26 following features: low cost fabrication, low insertion loss (high efficiency), fully  
27 integrated design with no free-space optics, general spatial wavefront transformation  
28 capability, general spectral transformation capability, and multiport operation with  
29 capability of distinct spectral/temporal and spatial transfer functions connecting  
30 operative port pairs.

1 **SUMMARY**

2 **[0019]** Method and apparatus are disclosed for receiving from an input an optical  
3 signal in a volume hologram comprising a plurality of diffractive elements comprising  
4 temporal and/or spectral transformation information and may also comprise spatial  
5 transformation information; diffracting the optical signal via the diffractive elements  
6 producing a diffracted optical signal; and producing an output comprising the diffracted  
7 optical signal.

## BRIEF DESCRIPTION OF THE DRAWINGS

[0020] Fig.1 (prior art) shows an input signal  $E_{in}(t)$  accepted by a spectral filtering device comprising a transfer function  $T(\omega)$ , and a processed output signal  $E_{out}(t)$ .

[0021] Fig. 2 (prior art) shows data input from two sources, applying a spectral filter to each input, transmission and subsequent decoding.

[0022] Fig. 3 (prior art) shows a dual-grating, free-space spectral filter design.

[0023] Fig. 4 (prior art) shows a programmed surface-grating spectral filtering device.

[0024] Fig. 5 (prior art) shows a programmed fiber-Bragg grating spectral filtering device.

[0025] Fig. 6 shows the basic geometry of a planar waveguide appropriate to contain a programmed planar holographic spectral filtering device, according to one embodiment of the invention.

[0026] Fig. 7 shows a substrate for a programmed planar holographic spectral filtering device, mounted between support slabs, according to one embodiment of the invention.

[0027] Fig. 8 shows a programmed planar holographic spectral filtering device with one input and one output, according to one embodiment of the invention.

[0028] Fig. 9A shows a programmed planar holographic spectral filtering device with one input and multiple outputs, according to an embodiment of the invention.

[0029] Fig. 9B shows a programmed planar holographic spectral filtering device with multiple inputs, according to an embodiment of the invention.

[0030] Fig. 10 shows a programmed planar holographic spectral filtering device according to one embodiment of the present invention, indicating the geometry of diffractive elements.

[0031] Fig. 11 shows a programmed planar holographic spectral filtering device with multiple inputs and outputs, according to an embodiment of the invention.



- 1   **[0032]** Fig. 12 shows a programmed holographic spectral filtering device configured as  
2           an optical waveform cross-correlator, according to one embodiment of the  
3           invention.
- 4   **[0033]** Fig. 13 illustrates a calculational method employing interference between a  
5           stimulated input and output signal pulse used in programming according to an  
6           aspect of the invention.

## 1 DETAILED DESCRIPTION OF EMBODIMENTS

2 **[0034]** The present invention contemplates a new class of spectral filtering devices,  
3 which we refer to as programmed holographic spectral filtering devices, or more simply  
4 and interchangeably as programmed holographic devices or programmed holographic  
5 processors. These spectral filtering devices are free of the shortfalls of previous  
6 spectral filtering devices, and yet provide low cost, high performance functionality.  
7 Programmed holographic devices comprise volume holograms in substrates that may  
8 comprise planar waveguides, bulk materials, or other substrates, whose diffractive  
9 elements have spatial variations in amplitude, optical spacing, or spatial phase, whose  
10 detailed form dictates the transfer function produced by the device. A volume hologram  
11 is a diffractive structure operative to generate output optical signals in response to input  
12 optical signals, wherein each portion of the wavefront of the input signal contributes to  
13 the output signal by scattering from the diffractive structure as it propagates through the  
14 structure over a distance large enough so that retardation effects within the diffractive  
15 structure significantly influence the form of the output signal. A volume hologram  
16 contrasts with a surface or thin hologram as follows: for a volume hologram, each  
17 portion of the input signal wavefront contributes to the output signal due to scattering by  
18 a diffractive structure distributed on and within a volume; for a surface or thin hologram,  
19 each portion of the input signal wavefront contributes to the output signal only by  
20 scattering from a thin layer of diffractive structure.

21 **[0035]** Filtering devices after the present invention provide for the control and  
22 modification of temporal, spectral, and spatial properties of input optical signals. The  
23 present invention comprises a spectral filtering device whose advantages include:

24 **[0036]** high efficiency, even when high-complexity transfer functions are required;

25 **[0037]** ability to impart general spectral transfer functions;

26 **[0038]** multiple input and output ports which are spatially separate from one another,  
27 thus eliminating the need for costly ancillary components such as circulators;

28 **[0039]** fast and economical fabrication through stamping, lithographic, or masking  
29 processes operative on an external surface;

1 **[0040]** ability to accept input signals with general planar or curved spatial wavefronts  
2 and transform them upon diffraction to other general planar or curved spatial  
3 wavefronts so as to match needed input and output wavefront parameters and  
4 eliminate separate wavefront conditioning components; and

5 **[0041]** capability for providing multiple spectral/temporal transfer functions in a single  
6 device.

7 **[0042]** In one embodiment, shown in Fig. 6, a programmed holographic device  
8 comprises a thin planar slice of substrate material having millimeter-to-centimeter-scale  
9 extent in the x- and y- directions (i. e. length and width dimensions of the planar  
10 surface), and a micron-scale extent in the z-direction (i. e. the thickness dimension of  
11 the planar slice). The extent 602 in the x-direction is of length L, the extent 604 in the  
12 y-direction is of width W, and the extent 606 in the z-direction is of thickness t. Input  
13 and output signals propagate within the planar holographic substrate in the x-y plane.  
14 The planar holographic substrate, or slab, is typically constructed of a material  
15 sufficiently transparent at the intended operational wavelength of the device so that  
16 unacceptable loss does not accrue from absorption as signals propagate through the  
17 programmed holographic device. Typical substrate materials include silica ( $\text{SiO}_2$ ),  
18 which is transmissive over much of the visible and near infrared spectral region;  
19 polymers; and silicon. Many materials capable of supporting volume holograms are  
20 known; any of these may be utilized as a substrate material for programmed  
21 holographic devices. The thickness of the planar substrate is preferably set to a value  
22 small enough to ensure that only a relatively small number of transverse (z) modes are  
23 allowed, or more specifically, that allowed transverse (z) modes do not experience  
24 significant modal dispersion on passing through the programmed holographic device.  
25 Stated another way, the maximal transit-time difference between supported z-modes is  
26 preferably substantially less than the temporal resolution that the programmed  
27 holographic processor is designed to provide. Yet another description of the preferred  
28 thickness is that the inverse of the maximal transit-time difference between supported z-  
29 modes is substantially less than the spectral resolution that the programmed  
30 holographic reflector is designed to support.

1 **[0043]** It is also preferable that modal propagation speeds of the planar modes  
2 significantly utilized by the device do not change significantly over the operative spatial  
3 extent of the programmed holographic structure. Raw substrates are preferably  
4 controlled to have refractive index and thickness homogeneity sufficient so that  
5 substrate modes accumulate a positional displacement of substantially less than one  
6 wavelength of light at the operative frequency, relative to a constant speed reference on  
7 passing from end-to-end through the operative programmed holographic structure.  
8 Variations in substrate thickness and index of refraction are completely acceptable in  
9 those instances where they are known and can be accounted for in the design of the  
10 programmed holographic structure.

11 **[0044]** Mechanical stability of the planar holographic substrate is typically enhanced  
12 when it is attached on one or both sides to support slabs 702, as shown in Fig. 7.  
13 Support slabs may be any dielectric whose index of refraction is suitably different from  
14 that of the holographic substrate, to ensure that at least one optical mode is primarily  
15 confined to propagate within the holographic substrate. Support slabs of metal may  
16 also be considered although some absorptive losses will accrue. Optical signals may  
17 be coupled into/out of a planar substrate 704 comprising the programmed hologram  
18 structure, via integrated optical waveguides or fibers (not shown) coupled to the edge of  
19 the substrate, or via prism coupling (not shown) in and/or out along the planar face(s) of  
20 the substrate. Waveguide or fiber inputs and outputs coupled to the edge of the  
21 substrate may be supported by an attachment strip along portions of the periphery of  
22 the planar substrate 704 between the support slabs 702.

23 **[0045]** The programmed holographic structure comprising the diffracting elements  
24 which effects the designed spectral, temporal, and/or spatial filtering, situated on or  
25 within the holographic substrate, may be take a variety of embodiments, with  
26 corresponding fabrication methods.

27 **[0046]** The diffractive elements may comprise profile variations in the planar boundary  
28 of a planar waveguide. In one embodiment, one or both faces of the substrate,  
29 (preferably only one), is etched by photolithographic, e-beam, or other standard surface  
30 etching means known in the art, to produce, e.g., a surface depth profile (depth here is

1 defined as the deviation of the local substrate surface from the average surface level),  
2 or, e.g., a refractive index profile comprising variations from the original substrate  
3 refractive index value, whose spatial structure comprises the diffractive elements of the  
4 programmed holographic structure.

5 **[0047]** In another embodiment, one or both slab faces may be deformed by the  
6 application of a stamp or other mechanism, whose surface relief has the spatial  
7 structure of the desired programmed holographic structure. In yet another embodiment,  
8 a thin deformable dielectric layer, with thickness on the order of one micron, may be  
9 deposited on one or both faces of the substrate, followed by deformation of the thin  
10 dielectric layer(s) by, e.g., a stamp or other mechanism whose surface relief has the  
11 spatial structure of the desired programmed holographic structure. It is to be noted that  
12 the similarity in refractive index between the thin dielectric layer and the substrate is  
13 important. For a fixed surface relief geometry derived from deformation of an overlayer,  
14 the coupling between input and output signals tends to be enhanced when the  
15 difference in refractive index of the overlayer and holographic substrate is minimized.  
16 More generally, control of the difference in refractive index between overlayer and  
17 holographic substrate provides for control over the input-output signal coupling strength.

18 **[0048]** In yet another embodiment, a metallic or dielectric layer whose surface relief  
19 has the spatial structure of the desired programmed holographic structure may be  
20 deposited on one or both of the grating slab faces. In yet another embodiment, one or  
21 both support slabs whose surface relief has the spatial structure of the desired  
22 programmed holographic structure, may be pressed securely against the substrate, and  
23 preferably bonded. In yet another embodiment, a planar substrate exhibiting  
24 photosensitivity leading to index or absorptive changes, may be exposed to writing  
25 optical fields propagating within the substrate and having the characteristics of the  
26 design optical fields described below. In yet another embodiment, a planar substrate  
27 exhibiting photosensitivity leading to index or absorptive changes, may be exposed, via  
28 contact or projection imaging, to an optical writing field whose spatial intensity pattern  
29 within the substrate conveys the spatial structure of the desired programmed  
30 holographic structure.

1 **[0049]** Additionally, there exist a large number of methods known in the art for applying  
2 approximately periodic structures to the surfaces or interiors of substrate materials,  
3 including but not limited to lithography/etch, electron beam lithography, abrasive  
4 material removal techniques, laser ablation, photolithography, mechanical ruling,  
5 masking, stamping, pressing, and embossing. Use of any of these methods to make  
6 volume holograms that apply dielectric perturbations to optical waves propagating within  
7 the holographic substrate falls within the scope and spirit of this invention.

8 **[0050]** The programmed holographic structure, written on or within the planar  
9 substrate, diffracts the signals incident from one or more input ports to one or more  
10 output ports while simultaneously applying a programmed spectral transfer function.  
11 Fig. 8 shows an embodiment 800 of a planar programmed holographic processor, 802  
12 with a single input port 804 and a single output port 806. An input optical signal  
13 expands from the fiber or waveguide input port 804 as shown. As it propagates, it is  
14 diffracted backwards and focused onto the output port 806. The back diffraction  
15 process acts further to apply the design spectral transfer function. The spacing  
16 between the input and output ports,  $d$ , is conveniently made as small as possible, with a  
17 typical separation of between about 25 to about 5000 microns. The output port 806 and  
18 the input port 804 do not have to be close, but placing them thusly provides for the  
19 highest spectral resolution possible for a fixed device length  $L$ . For a device length of  $L$ ,  
20 the spectral resolution available with closely spaced input and output ports is roughly  
21  $v_s/2L$ , where  $v_s$  is the speed of light in the utilized  $z$ -modes of the holographic substrate.  
22 Spectral resolution is degraded by refractive index or thickness variations of the  
23 holographic substrate, unless compensated for in the design of the programmed  
24 holographic structure. Actual resolution from a device possessing uncompensated  
25 refractive index or thickness variations can be estimated by replacing the actual device  
26 size  $L$  in the formula above with an effective length given by the distance over which  
27 actual optical signals within the programmed holographic structure remain coherent with  
28 a reference wave that propagates at constant speed. In Fig. 9A a planar programmed  
29 holographic structure having an input 902 and multiple outputs 904 is shown. Each of  
30 a plurality of signals transmitted from an input 902 (there may be one or more than one  
31 signal sent to each output) to outputs 904 experiences a different transfer function. The

1 configuration shown in Fig. 9A may serve as a wavelength-based or temporal-  
2 waveform-based demultiplexer; the configuration shown in Fig. 9B, may serve as a  
3 multiplexer having inputs 922 and an output 920.

4 **[0051]** In a programmed holographic device configured as a demultiplexer shown in  
5 Fig. 9A, the programmed holographic structure directs one or more specific  
6 wavelengths incident from the input port, to each of the output ports. The programmed  
7 holographic structure needed to do this comprises the sum of the structures that would  
8 individually map only specific wavelengths from the input port to one of the output ports,  
9 the holographic structure not appreciably interacting with those wavelengths not  
10 directed to that specific output port.

11 **[0052]** A programmed holographic structure that maps input signals from one input  
12 port to one output port is referred to as a primitive programmed holographic structure, or  
13 a primitive structure. The overall distributed diffractive (holographic) structure of a  
14 device which may map multiple input ports to multiple output ports, and is the sum of  
15 one or more primitive structures, is referred to its programmed holographic structure.  
16 The primitive programmed holographic structures may occupy spatial regions that are  
17 the same, partially overlapping, or non-overlapping. The output ports are typically  
18 positioned at respective conjugate image points to the input port. A pair of conjugate  
19 image points is defined by the relationship that certain spectral components of a signal  
20 emanating from one point are focused by the spatial transfer function of the  
21 programmed holographic structure to the conjugate image point; furthermore the two  
22 points act reciprocally, so that the same spectral components within a signal emanating  
23 from the second point are focused by the transfer function onto the first. Primitive  
24 programmed holographic structures comprising diffractive elements in the form of e.g.,  
25 circular, elliptical, parabolic or other focusing contours, can be employed to produce  
26 reciprocal focusing between conjugate points. Fig. 10 shows a set of diffracting  
27 elements 1002 which have circular contours, and conjugate points 1004, 1006. Owing  
28 to the general wavefront transformation capability of holographic structures, a wide  
29 range of input/output geometries can be accommodated. Rather than implementing  
30 programmed holographic structures that simply map signals from one point onto

1 another and the reverse, it is possible to configure the programmed holographic  
2 structure so as to map an arbitrary input wavefront into an arbitrary output wavefront.

3 **[0053]** In Figure 11, a planar-programmed holographic device 1100 with a different  
4 configuration is shown. In this configuration there are two inputs 1102, 1104, and three  
5 outputs 1106, 1108, 1110. The transfer function of the programmed holographic  
6 structure 1112 can be designed so that signals from the inputs 1102 and 1104 are  
7 directed at one or more of the outputs 1106, 1108, 1110, with each port-to-port  
8 connection having an individual spectral/temporal transfer function that may be the  
9 same or different than the others. Individual port-to-port connections are controlled by  
10 primitive programmed holographic structures.

11 **[0054]** In Figure 12, a programmed holographic device 1200 is shown, configured as  
12 an optical waveform cross-correlator. A holographic substrate 1202 is mounted to a  
13 support slab using an attachment strip 1204. An input fiber 1206 guides an input signal  
14 1210  $E_i(t)$ , having Fourier spectrum  $E_i(\omega)$ , into the holographic substrate to interact with  
15 the *programmed holographic structure contained therein*. An output signal 1212,  $E_{out}(t)$   
16 produced by back diffraction from the programmed holographic structure within or on  
17 the substrate, is fed into an output fiber 1208. The holographic structure 1200 is  
18 programmed so that its spectral transfer function is  $E_d^*(\omega)$ , where  $E_d(\omega)$  is the Fourier  
19 transform of a design matching input signal  $E_d(t)$ . The output signal whose electric field  
20 is proportional to the integral, over the frequency  $\omega$ , of the product  $[E_d^*(\omega) \cdot E_i(\omega)]$ ,  
21 represents the cross correlation of  $E_i(t)$  with  $E_d(t)$ .

22 **[0055]** A primitive programmed holographic reflector/processor comprises a plurality of  
23 diffraction elements, each of which typically corresponds to a contour of constant index  
24 of refraction, a depth contour of a surface relief, or other physical element known in the  
25 art to produce diffracted signals. The spatial structure of the diffractive elements  
26 contains the programming information that allows it to map an input port to an output  
27 port, with a specific spectral transfer function.

28 **[0056]** The spatial structure of the diffractive elements needed to produce specific  
29 spectral transfer functions can be determined in a variety of ways. The spatial structure  
30 of a primitive programmed hologram can be calculated as an interference pattern



1 generated by the collision of two optical pulses of appropriate spatial wavefront and  
2 temporal profile. As shown in Fig. 13, a simulated input pulse 1302 whose temporal  
3 shape is given by  $E_{si}(t)$ , collides with a simulated output signal pulse 1304 whose  
4 temporal shape is given by  $E_{sout}(t)$ . The calculation models the propagation of the two  
5 pulses as they pass through each other, and the electric-field interference pattern that  
6 they produce. In one calculational approach, the simulated input pulse is launched from  
7 the location of the input port, with a spatial wavefront appropriate to emission from a  
8 point source. The simulated output pulse is launched toward the location of the output  
9 port so as to completely or partially overlap the path of the simulated input pulse, with a  
10 spatial wavefront that provides for aperture-limited, i.e., diffraction-limited, spot size at  
11 the location of the output port. The central wavevectors of the simulated input and  
12 output pulses make an angle relative to each other. This angle is preferably greater  
13 than 90 degrees and more preferably close to 180 degrees. The actual value of the  
14 angle is set by the constraints that the simulated pulses at least partially overlap and by  
15 the location of the input and output ports. In modeling the propagation of the simulated  
16 input and output pulses, variation of field amplitude is preferably suppressed. In the  
17 case of planar holographic devices, both simulated pulses propagate in the plane of the  
18 planar holographic substrate. In the case of bulk or three-dimensional devices, both  
19 pulses propagate through the bulk or three-dimensional substrate. If the primitive  
20 holographic structure is to be programmed to produce a spectral transfer function of the  
21 form  $E_i^*(\omega)$ , i.e. the complex conjugate of the Fourier transform of the real temporal  
22 function  $E_i(t)$ , the simulated input pulse is given the temporal waveform  $E_i(t)$ , i. e.  $E_{si}(t)$   
23  $= E_i(t)$ , and the temporal waveform of the output pulse,  $E_{sout}(t)$ , is such that its total  
24 temporal duration is substantially shorter than the inverse of the overall spectral  
25 bandwidth of  $E_i^*(\omega)$ ; equivalently, the simulated output pulse should have a temporal  
26 duration substantially shorter than the inverse of the overall spectral bandwidth of the  
27 simulated input pulse. One convenient form for the output temporal profile is a  
28 transform-limited brief pulse satisfying the bandwidth constraint cited above. Note that  
29 the evolution of the full electric field of each simulated pulse, i.e., carrier frequency plus  
30 envelope, is followed through the simulated propagation. The optical carrier frequency  
31 of the simulated output signal is made coincident with that of the simulated input signal.

1 The common optical carrier frequency of the two simulated pulses controls the optical  
2 frequency at which the primitive programmed holographic structure is operative. The  
3 times at which the simulated input and output signals pass through their respective  
4 ports are controlled so that the two simulated pulses pass through each other, i.e.,  
5 collide, while inside the physical boundaries of the holographic substrate. The  
6 holographic substrate will optimally have a physical length of at least  $v_s \tau_1 / 2$ , where  $v_s$  is  
7 the speed of light in the substrate and  $\tau_1$  is the temporal duration of the simulated input  
8 pulse in order to best record the programming structure. The electric field interference  
9 pattern calculated as the two simulated pulses collide, is mapped to variations in index  
10 of refraction, surface depth, or other parameter as might be appropriate to characterize  
11 the specific type of diffractive elements employed in the hologram design. To create a  
12 general transfer function  $T(\omega)$ , the calculation method described above is implemented  
13 with an simulated input signal having the spectrum  $T^*(\omega)$  with the simulated output pulse  
14 chosen as above. The temporal profile of the general simulated input pulse is derived  
15 from  $T^*(\omega)$  by Fourier transformation.

16 **[0057]** It may be useful to note that the impulse response, i.e., the temporal output  
17 waveform produced in response to a temporal delta function injected into the input port,  
18 of a primitive programmed holographic structure designed according to the method  
19 disclosed supra, is  $E_i(-t)$ , i. e. the time-reverse of the simulated input pulse.

20 **[0058]** As an alternative to the calculational procedure outlined above, the temporal  
21 waveforms of the simulated input and output pulses called out above may be  
22 interchanged. In this case, the spectral transformation produced by a primitive  
23 holographic structure programmed according to the calculated interference pattern will  
24 be  $E_i(\omega)$ , and the impulse response will be  $E_i(t)$ .

25 **[0059]** The wavefronts of the simulated input and output functions can be modified  
26 from the forms specified above to provide more efficient coupling of input signals to the  
27 output port employed. Let  $E_{ir}(\mathbf{r})$ ,  $E_{out}(\mathbf{r})$ ,  $E_{si}(\mathbf{r})$ , and  $E_{sout}(\mathbf{r})$  be, respectively, the spatial  
28 wave generated by the input port, the spatial wave optimally matched to the output port,  
29 the spatial wave used as the simulated input, and the spatial wave used as the  
30 simulated output. The parameter  $\mathbf{r}$  represents the vector position within the holographic

1 substrate.  $E_{ir}(\mathbf{r})$  and  $E_{out}(\mathbf{r})$  are fixed by the port characteristics and the waveguide or  
2 medium to which they couple. The functions  $E_{si}(\mathbf{r})$  and  $E_{sout}(\mathbf{r})$  are preferably chosen so  
3 that the following equation is satisfied:

$$4 \quad E_{out}(\mathbf{r}) = E_{ir}(\mathbf{r}) \bullet E_{si}^*(\mathbf{r}) \bullet E_{sout}(\mathbf{r}).$$

5 **[0060]** There are multiple calculational methods known in the art for designing the  
6 spectral transfer functions of fiber Bragg gratings. These methods can be applied to the  
7 design of programmed holographic structures of the present invention, by taking  
8 appropriate slices perpendicular to the diffractive elements, and approximating the  
9 design problem as having a single dimension. This approach will be most useful when  
10 input and output ports are closely spaced.

11 **[0061]** Programmed holographic structures capable of providing multiple port-to-port  
12 mappings are calculated as the sum of multiple primitive programmed holographic  
13 structures, each of which supports a single port-to-port mapping. As stated above, the  
14 primitive structures may be entirely overlapping, partially overlapping, or non-  
15 overlapping within the holographic substrate.

16 **[0062]** If the programmed holographic structures are to be fabricated by direct optical  
17 exposure of photosensitive holographic substrates, as in traditional holographic practice,  
18 the simulated signals described in the calculation method above correspond to the  
19 writing pulses needed. Writing may require large numbers of identical exposures, and  
20 may require full interferometric stability.

21 **[0063]** An important factor in the implementation of programmed holographic  
22 processors is the stabilization of their properties relative to changes in ambient  
23 temperature. The higher the spectral resolution demanded of programmed holographic  
24 devices, the greater will be the challenge of packaging them with adequate thermal  
25 stability. This is a common problem in optical devices wherein spectral response  
26 derives from physical structure. Great strides in thermal compensation have been  
27 made in the case of thin film and fiber grating devices. Many of those same  
28 compensation/stabilization methods can be applied to programmed holographic spectral  
29 filtering devices. Alternatively, simple reference diffractive structures can be designed

1 into the devices, whose output provides a feedback key for active stabilization of the  
2 devices to the frequencies of input optical signals, or to reference optical signals.

3 **[0064]** Having illustrated and described the principles of the invention in the above-  
4 described embodiments, it should be apparent to those skilled in the art that the  
5 embodiments can be modified in arrangement and detail without departing from such  
6 principles. In view of the many possible embodiments to which the presented may be  
7 applied, it should be recognized that the illustrated embodiments are only examples of  
8 the invention and should not be taken as a limitation on the scope of the invention.

9 Rather, the invention is defined by the following claims. It is therefore claimed as the  
10 invention all such embodiments that come within the scope and spirit of these claims.